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Physiological Responses and Thermal Comfort of Subjects in a Tractor Cab

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PHYSIOLOGICAL RESPONSES AND THERMAL COMFORT

OF SUBJECTS IN A TRACTOR CAB

BY

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OF SUBJECTS IN A TRACTOR CAB

This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Thesis Advisor Date

Head, Agricultural Engineering Department Date

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Chapter 1

THE PROBLEM

Introduction

Today there is a strong trend in the United States and Canada toward purchasing a cab with a new tractor or combine. Approximately 70 to 80% of the larger tractors (130-330 KW) leaving the factories have cabs. The majority of these tractor cabs purchased have refrigerated air-conditioning, although it is usually optional (9).

In order to use refrigerated air-cooling effectively to reduce heat build-up in tractor cabs, guidelines and indices must be developed to evaluate thermal comfort. The conditioning and control of air in an agricultural tractor cab is a relatively new field. Most of the research which has been done applies to the conditions in offices where the mean radiant temperature equals the air temperature and air velocities are less than 45 feet per minute. Operators in tractor cabs may be exposed to high radiant temperatures and high air velocities. Therefore, guidelines and indices are needed for establishing thermal comfort in cabs.

Objectives

P. O. Fanger of Denmark was the first scientist to generalize the physiological basis for predicting human thermal comfort based on activity level, clothing type, air temperature, air velocity, mean radiant temperature, and air humidity. Thus for any activity level and clothing type, it is possible to determine combinations of air temperature, mean radiant temperature, air humidity and relative air velocity which would produce optimum thermal comfort. The Fanger approach has been applied successfully to offices and buildings. It would be quite useful to demonstrate that Fanger's concepts could be applied to tractor cabs.

When determining the activity level it is also important to determine what effect various environmental parameters might have on it. It is important to determine the effect of these parameters because of conflicting evidence in the literature. According to Nelson *et al.* (21), "Metabolic heat production for a given amount of work remains unchanged irrespective of change in environmental conditions." Whereas, according to Suggs and Splinter (28),

> It can be concluded from the prediction equations derived from the experiments in which temperature, relative humidity, and workload were simultaneous independent variables that the subject's heart rate, ventilation rate and oxygen consumption rate responded in similar manner. Each of these three responses increased quite rapidly with respect to workload and at about one-half to one-third that rate with respect to temperature. Relative humidity, with a small first-order effect, interacted with temperature so as to depress temperature effects at low relative humidity values.

Therefore, these parameters should also be investigated to see if they have any effect on the activity level readings which are recorded.

The objectives of this study were as follows:

1. Determine the effect of cab air temperature and velocity on physiological parameters within a tractor cab for summer conditions.

2. Determine if Fanger's criteria for thermal comfort is applicable to tractor cabs for summer conditions.

Chapter 2

RELATED STUDIES

Thermal Comfort of the Operator

Heat Balance Equation

Thermal comfort is defined as "the state of mind which expresses satisfaction with the thermal environment" (2). Expressed mathematically, the heat exchange necessary for thermal comfort between man and his environment may be described by the general heat balance equation:

$$M = \pm E \pm C \pm R \pm S \pm W$$

where

M = heat production in the body (metabolism)

E = heat exchange by evaporation

C = heat exchange by convection

R = heat exchange by radiation

S = heat stored in the body

W = mechanical work accomplished

Positive values for E, R, and C will all cause the mean body temperature to rise; negative values will cause it to fall. A positive value for S indicates that the average body temperature is rising; when negative, it is falling; and when zero, the body is in thermal equilibrium. "Work W is positive when accomplished by the body (eg. walking up steps) and this potential energy must be subtracted from the body energy produced (M) to find the net heat developed within the body core. When

W is negative (walking down steps), this heat is added to the body system" (2).

Each term in the heat balance equation is conveniently described in terms of energy per unit area of body surface (eg. W/m^2, $Kcal/hr\text{-}m^2$, or $BTU/hr\text{-}ft.^2$) since heat exchange--whether by radiation (R), convection (C), or vaporization (E)--is always related in some way to the body's surface area. The most common measure of body surface area has been proposed by DuBois (2). It is described by the formula

$$BSA = 0.203X10^4 \; w^{0.425} \; h^{0.725}$$

where the DuBois body surface area (BSA) is in square meters, body weight (w) is in kilograms, and height (h) is in meters. Another measure of body surface area has been proposed by Boyd (5) and is described by the formula

$$BSA = (3.20 \; w^{0.7285 \; - \; .0188 \; \log w} \; h^{0.3}) \div 10^4$$

where body surface area (BSA) is in square meters, body weight (w) is in grams, and height (h) is in centimeters.

Indices Used to Evaluate Thermal Comfort

There are three classes of environmental indices: (a) the direct, (b) the rationally direct, and (c) the empirical.

The direct indices are common terms to most engineers. They are the dry-bulb temperature, dew point temperature, wet-bulb temperature, relative humidity, and air movement.

Some of the rationally derived indices are mean radiant temperature, operative temperature, and humid operative temperature. The mean radiant temperature is defined as "the uniform surface temperature of an imaginary black enclosure with which man (also assumed a black body) exchanges the same heat by radiation as in the actual environment" (2). The operative temperature is defined as "the uniform temperature of an imaginary enclosure with which man will exchange the same dry heat by radiation and convection as in the actual environment" (2). Humid operative temperature is defined as "the uniform temperature of an environment at 100% relative humidity with which a man will exchange the same heat from his skin surface by radiation, convection, conductance through clothing, and evaporation as in the actual environment" (2).

Three common empirical indices are the wind chill index, black globe temperature and effective temperature. The wind chill index was developed by Paul Siple in 1948 for use by the U. S. Army while in Antarctica. It is an empirical equation which describes the rate of heat loss from a liter cylinder of water at 33° C (91.4° F) as a function of ambient temperature and wind velocity. There has been some objection to the wind chill index because it reaches a peak value at 56 mph and then decreases; but for velocities less than 50 mph this index has been reliable (2). The black globe temperature combines the physical effects of dry-bulb temperature, air movement, and radiant heat received from various surrounding area. It is determined by taking the equilibrium temperature of a 6 inch diameter black globe (2). Effective temperature is an index which combines the effect of dry-bulb temperature, wet-bulb temperature, and air movement to yield equal sensations of warmth or cold (2). This scale "overemphasizes the effect of humidity in the cooler conditions, underemphasizes the effect of humidity in the warm conditions and does not fully account for air velocity under hot-humid conditions. Finally, its use is limited to sedentary conditions" (2).

Guidelines for Thermal Comfort

The first single temperature scale, which was used to measure thermal comfort of the environment, was developed by Houghton and Taylor in 1923. This index of thermal comfort was called effective temperature (ET). The results of this study combined the effects of dry-bulb temperature, wet-bulb temperature and air motion on a single chart (15).

An American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) comfort chart was published in 1925. Since that time, a note has been added which defines its application.

> Both summer and winter comfort lines apply to inhabitants of the United States only. Application of winter comfort line is further limited to rooms heated by central systems of the convection type. The line does not apply to rooms heated by radiant methods. Application of summer comfort line is limited to homes, offices, and the like, where the occupants become fully adapted to the artificial air conditions. The line does not apply to theatres, department stores, and the like where the exposure is less than 3 hr. The summer comfort line shown pertains to Pittsburgh and to other cities in the Northern portions of the United States and Southern Canada, and at elevations not in excess of 1,000 ft. above sea level. An increase of one deg ET, should be made approximately per 5 deg. reduction in north latitude (22).

As early as 1950 plans were made by the American Society of Heating and Ventilation Engineers (ASHVE) to reevaluate the comfort chart. A study by Koch, Jenning and Hemphreys (16) was the first step toward reevaluation of the comfort chart. The results showed that over the range of variables studied, comfort is only slightly dependent on humidity and the optimum comfort line is approximately straight and ranges from 77.6^{o} F at 30% relative humidity to 76.5^{o} F at 85% relative humidity.

In 1966, Nevins and his colleagues (23) defined a new comfort line. His results showed there was a strong linear effect of temperature and a smaller linear effect of relative humidity (R. H.) on thermal comfort, an interaction effect between temperature and R. H. was statistically significant, and that there was no significant difference between afternoon and evening tests.

In 1972, a new comfort chart was published by ASHRAE. It included the comfort envelope from the KSU-ASHRAE project, the comfort zone recommended in the ASHRAE Comfort Standard 55-66 and the new Effective Temperature Scale (ET*) based on a simple model of human physiological response. This comfort chart "applies generally to altitudes from sea level to 7,000 ft. and to the most common special case for indoor thermal environments in which mean radiant temperature is nearly equal to dry-bulb air temperature and air velocity is less than 45 fpm" (2).

Fanger's Comfort Equation

P. O. Fanger (13), from the Technical University of Denmark, was the first person to generalize the physiological basis of comfort so that for any activity level and clothing value it is possible to analytically predict comfort in terms of environmental parameters. His comfort equation is based on three basic conditions for optimum thermal comfort. The first condition is based on the existence of a heat balance at thermal equilibrium (body heat storage equals zero). In functional notation it takes the following form:

$$F(H/A_{Du}, I_{cl}, t_a, t_{mrt}, p_a, v, t_s, E_{sw}/A_{Du}) = 0$$

where

H/A_{Du} = internal heat production per unit body surface area (A_{Du} = DuBois Body Surface Area)

I_{cl} = thermal resistance of clothing

t_a = air temperature

t_{mrt} = mean radiant temperature

p_a = pressure of water vapor in ambient air

v = relative air velocity

t_s = mean skin temperature

E_{sw}/A_{Du} = heat loss per unit body surface area by evaporation of sweat secreation

The second and third basic conditions for comfort are based on experimental observations that during a state of comfort a unique relation exists between the level of activity and mean values of skin temperature and sweat secretion. The results have the following form:

$$t_s = F\,(H/A_{Du})$$

$$E_{sw} = A_{Du}\, F(H/A_{Du})$$

By substituting the conditions for skin temperature and sweat secretion into the heat balance condition, the desired comfort equation takes the following form:

$$F\,(H/A_{Du}, I_{cl}, t_a, t_{mrt}, p_a, v) = 0$$

Thus for any activity level (H/A_{Du}) and any clothing (I_{cl}) it is possible to calculate any combination of air temperature (t_a), mean radiant temperature (t_{mrt}), air humidity (p_a), and relative air velocity (v) which would produce optimum thermal comfort.

Environmental Conditions in Small Enclosures

Most of the studies which have been done on thermal comfort have been concerned with the environment in buildings. Eriksson and Domier (11) made a comparison of the heat losses for a person in a building and a tractor cab for the same activity level and clothing and for outside conditions of -20^{o} C and 200 Pa. The comparison is as follows:

	Building	Tractor Cab
Radiation	40%	63%
Convection	40%	-3%
Evaporation	20%	40%

"This comparison shows the influence of the large glass surface area on the heat loss by radiation. The heat loss through evaporation and breathing increases markedly while the convective heat in this case must be supplied to the body to maintain a thermal balance" (11).

Domier (9), in a separate paper, also noted differences in environmental conditions in small enclosures such as a cab as compared to the most commonly recommended design conditions for comfort. An operator of a tractor may have an activity of two to three mets depending on the physical effort involved. However, the 1972 ASHRAE

Comfort Chart is designed for an activity level range of 1.0 to 1.4 mets. According to the Fanger Comfort Chart, an increase in activity level from one to two mets will require a decrease in temperature of 6^{o} to 9^{o} C depending on the clothing worn. Similarily, changing from light clothing (0.5 clo) to heavy clothing (1.5 clo) will require a decrease in temperature of 5^{o} C at an activity level of one met and a decrease of 9^{o} C at an activity level of two mets. Lastly, the distribution of air in a cab may result in air velocities that are objectionable to the operator.

Thermal Comfort of Subjects in Tractor Cabs

Some studies have been completed which deal specifically with the thermal comfort of subjects in tractor cabs. In a study by Turnquist and Thomas (30), 85 male subjects participated in a tractor cab subjective comfort study. Each subject spent 50 minutes inside the cab in order to evaluate one of five levels of dry-bulb temperature settings. Each subject rated their comfort on a scale of 1 to 7 (4 being comfortable) and these ratings were compared to various indices such as wet-globe temperature, effective temperature, ambient temperature and the 1972 ASHRAE comfort chart. The results showed that ambient temperature at the occupant shoulder height was a better indicator of comfort than effective temperature or wet-globe temperature. Eriksson and Domier (11) have done work on the comfort of subjects in heated tractor cabs. In their investigation a test panel of 15 persons were used to evaluate conditions for thermal comfort. The subjects were exposed to the cab environment for 2.5 hours with a work level of about 90 W/m^2 being generated by pedalling a special bicycle ergometer for 5 minutes with 5 minute rest intervals. Two types of clothing were used (1.5 clo and 2.0 clo), and the subjects stated at which cab temperatures they felt comfortable. A comparison of the cab temperature chosen by the subject to a calculated comfortable temperature based on Fanger's comfort equation was made. The spread in data was quite large. "This may indicate that the comfort equation is applicable only to an average group of people. The variation between individuals therefore places increased demands on the whole heating and ventilating system to provide the conditions desired by the operator" (11).

Measuring Metabolism

Calorimetry is the process of measuring quantities of heat production. Lavoisier, considered the founder of the modern science of nutrition, began the measurement of metabolic energy in the late 18th century. He placed a guinea pig in a very small closed chamber surrounded by ice. Attempting to quantify animal heat production, the degree of melting became his index of metabolic activity. He also measured his subjects' respiratory exchanges and soon demonstrated a significant relationship between oxygen uptake and heat output. This relationship is now well understood. Food enters the body as stored energy. It is liberated by oxygen in order to fuel bodily functions. This process is known as oxidation. The energy facilitates muscular work, chemical synthesis, and ionic balance and is ultimately reduced to heat. Thus, metabolic activity can be determined directly through the output of heat or indirectly through the intake of oxygen (26).

Direct Calorimetry

Direct calorimetry is difficult and costly in practice though easy in theory. "If an animal or man is put into a small chamber in which all the heat evolved can be measured, the total energy expenditure is the sum of that heat plus any mechanical work performed" (8).

In 1892, Atwater began work on a chamber which permitted both direct and indirect measurement of heat production in man. This calorimeter was a closed room containing a couch and bicycle ergometer. Food was passed in and excreted out through a small hatch. All body heat was taken up by water circulating in pipes throughout the calorimeter. Thus the energy output of the subject was determined by the rise in water temperature. Simultaneously, indirect measurements were made through a closed respiratory system (26). Two conclusions were reached using the Atwater calorimeter (8):

1. Total energy expenditure (the sum of the heat produced plus the mechanical work done) was equal to the net energy from the food consumed (the total chemical energy in the food minus the energy lost in the faeces and urine). They left no doubt that man obeys the fundamental physical law of the Conservation of Energy.

2. Total energy expenditure is quantitatively related to the oxygen consumption.

In other words, indirect calorimetry proved to be nearly as accurate as direct calorimetry.

Indirect Calorimetry

Indirect calorimetry is the measurement of oxygen consumption. It is a far simpler procedure than direct calorimetry and has for many years replaced direct calorimetry in the study of energy expenditure. "It is based on the fact that when an organic substance is completely combusted either in a calorimeter or in the human body, oxygen is consumed in amounts directly related to the energy liberated as heat" (8). Lusk (17) states that the quantity of oxygen required in metabolism depends on the kind of material oxidized in the organism and the relation between the amount of oxygen absorbed and carbon dioxide eliminated depends on the same factor. The ratio of the volume of carbon dioxide expired to the volume of oxygen inspired during the same interval of time is called the respiratory quotient (RQ). The RQ varies with the diet. If the comparative amounts of carbohydrate, protein, and fat are known, an RQ can be estimated. Accurate data is obtained by measuring both O_2 and CO_2 under calorimetry conditions. However, Brody (6) points out that

> ...while the range in caloric equivalents of CO_2 is relatively wide, from 5.0 to 6.7 Cal. per liter, the range of caloric equivalents of O_2 is relatively narrow, from 4.7 to 5.0 Cal per liter, an extreme range of 7 percent, or a deviation of about 3.5 percent from the mean value (when the RQ is 0.82), which is within the limits of experimental error in metabolism measurements.
>
> Furthermore, since the average RQ of protein is 0.82, which corresponds to the average caloric value of O_2 of 4.825 Cal per liter, no correction need be made for protein metabolism when measuring energy consumption by oxygen consumption (6).

Therefore, the simplest and perhaps the most accurate method for measuring energy metabolism is by measuring the rate of oxygen consumption and computing the heat production by the caloric value of oxygen.

Most measurements of oxygen uptake are made when the subject is breathing into some form of apparatus which can measure the total volume of gas expired and provide a sample of the expired air for analysis. Valves are used to separate the inspired air from the expired air. These valves may be housed in a small metal or plastic box with a rubber mouthpiece which the subject grips between his teeth or they may be housed in a rubber mask covering the face (8).

Measurement of the respiratory exchanges may take two forms--the open method and the closed method. In the open method, the subject breathes in normal room air and his expired air is collected, its volume measured, and a sample taken for analysis. In the closed method, the subject breathes entirely both into and out of the apparatus and is completely cut off from the atmospheric air.

The most common apparatus utilizing the closed circuit method for measuring oxygen uptake is the Benedict-Roth Spirometer. At the start, the apparatus is filled with oxygen from a cylinder. This raises the spirometer bell, which floats on a water seal. The subject breathes through a mouthpiece. Valves are used to separate the inspired air from the expired air, which circulate through the spirometer. A canister containing soda lime absorbs the carbon dioxide produced. The volume of gas in the spirometer decreases as the subject uses up oxygen. The bell falls slowly and the fall is recorded by an ink-writing kymograph driven by a motor. The tracing gives a record of the rate of utilization of oxygen (18).

Many different types of open circuit systems have been designed. The Douglas gas system measures rates of oxygen uptake and carbon dioxide excretion. The subject breathes in ordinary room air and expires air to a huge bag where it is collected. This expired air is then passed through a gas meter, measured and a proportion set aside for analysis of oxygen and carbon dioxide content. This method is the simplest and most reliable means of measuring respiratory exchanges in the laboratory. However, it is somewhat uncomfortable for the subject and lacks mobility for experiments in the field (8).

In the 1920's the Max Planck respirometer was developed at the Planck Institute for Work Physiology in Dortmund, Germany. The apparatus was a portable respirometer, weighed about 5 pounds, and could be worn on the back. It could measure the volume of expired air directly and simultaneously divert a small fraction into a bladder for subsequent analysis. Its introduction made it possible to measure the energy expended in a variety of normal occupations (8).

Chapter 3

PROCEDURES

Overview

After reviewing the literature, it is apparent that guidelines and indices for comfort in tractor cabs need to be developed. Fanger's ideas seem applicable. However, in designing the experiment a conflict arises from the literature in regard to the effect of environmental parameters on the measurement of the activity level. Therefore, this area needs to be studied before the relevance of Fanger's equations can be studied. With these ideas in mind, the study was divided into two parts.

Part I

Tests were conducted to determine the influence of air temperature and air velocity on heart rate, pulmonary ventilation, oxygen consumption, and metabolic rate of subjects in a tractor cab. A split-plot design was chosen. Three levels of temperature (18°, 24° and 30° C) were used as whole plots. Three levels of air flow (8.5, 12.5 and 16.5 m^3/min) were varied randomly at a given temperature to give the subplots. The split plot design allowed greater accuracy in determining differences due to different air velocity levels. Less accuracy was associated with differences due to different temperature levels.

Part II

Tests were conducted to determine the applicability of Fanger's concepts to a tractor cab. Subjects were allowed to adjust the cab temperature to maintain comfort (thermal equilibrium) during a two hour test period. Each half hour, appropriate data of activity level, air humidity, air temperature, mean radiant temperature, relative air velocity and clothing were collected. Comfort levels from Fanger's equation were determined. Statistical analyses were performed to determine: (1) if differences existed in the votes of comfort calculated each half hour, and (2) if Fanger's criteria for comfort (Predicted Mean Vote) was acceptable in a tractor cab.

Physiological Measurements

Bicycle Ergometer

A Monark variable-load bicycle ergometer was used in this study to provide work levels for the subjects. Previous investigations have shown that subjects are familiar with this instrument. Hence, an increase in skill is minimized as an uncontrolled variable (10). The bicycle ergometer was placed in a position which allowed the pedals to be inside the cab and the load adjustment mechanism to be outside of the cab. See Figure 1. This allowed adjustment of the load without disturbing the subjects' environment.

Instruments used in conjunction with the bicycle ergometer provided additional accuracy in determining the subjects' workload. A Helipot one-turn rotary potentiometer was mounted on the pendulum as shown in Figure 2. The potentiometer was connected in a one-half wheatstone

Figure 1. Bicycle Ergometer Placement

Figure 2. Rotary Potentiometer Mounted on Bicycle Ergometer Pendulum

bridge to one channel of a two channel oscillograph (Offner Type RS). It was calibrated so that as the pendulum swung through a range of 1 kilopond on its indicator, the pen of the oscillograph deflected 20 lines (0.05 Kiloponds/line). A microswitch was mounted on the hub of the large wheel, as shown in Figure 3. A Beckman Model 6240 EPUT and Timer was used to determine the number of times the microswitch closed per second thus giving the speed of the wheel. The microswitch was also connected to one channel of the oscillograph through a double-pole double-throw switch. Thus it was possible to get a digital as well as a permanent readout of the speed of the wheel. Hence, thinking of the ergometer as a Prony Brake the workload was determined by using the following formula:

Workload (kilopond-meters/min) = Tension (kiloponds)

x Speed (Rev/sec) x 1.625 meters/rev x 60 sec/min

The seat in the cab was movable in a horizontal plane. This allowed the subjects to select the proper distance from the seat to the bicycle pedals.

Pulmonary Ventilation

An Ohio Midas face mask, shown in Figure 4, was used in this study. Two Collins one-way valves and a tee-joint were used to separate the inspired air from the expired air. On the inhalation side of the mask an Ohio Vortex Respiration Monitor transducer was attached. This flowmeter was calibrated with a Benedict-Roth spirometer and found accurate in the measurement of air flow. The pulmonary ventilation of each subject was obtained by direct reading of the

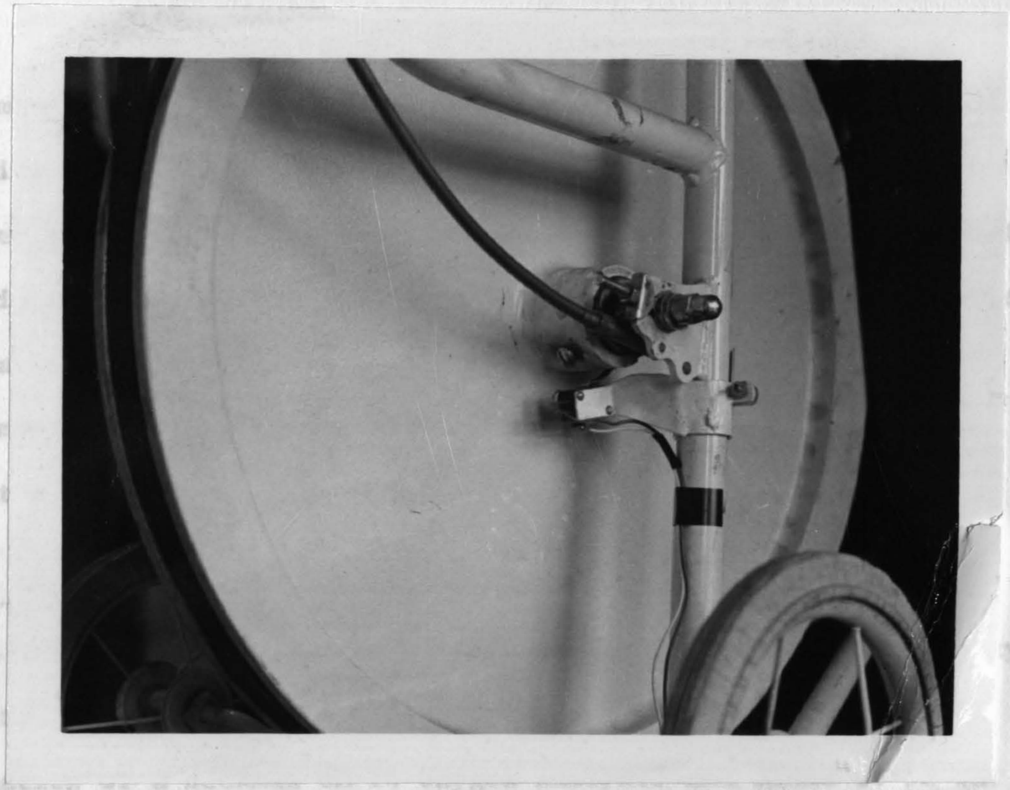

Figure 3. Microswitch on Bicycle Ergometer Wheel

Figure 4. Face Mask with Transducers

instrument. The instrument automatically reset itself to zero for each liter of air which passed through it. The test administrator observed the number of times the instrument recycled and recorded this value in addition to the readout of the instrument. The Ohio Vortex Respiration Monitor is shown in Figure 5. The transducer of this instrument may also be seen in Figure 4. It is the tube on the subject's left of the face mask.

Oxygen Analysis

A Teledyne Series 330 Portable Oxygen Monitor was used for oxygen analysis. The calibration of this instrument was compared to the calibration of a Beckman OM-14 Oxygen Analyzer and found to be in agreement. The instrument is shown in Figure 6. The transducer of the oxygen monitor is also shown on the subject's right of the face mask in Figure 4.

Heart Rate Recording Equipment

An E&M Physiograph Six was used to record the electrocardiograms of the subjects. For Part I, flat plate electrodes were used to receive the signal of the heart beating. See Figure 7. However, the plates shifted on the subjects as they pedalled. This caused the base-line of the electrocardiograms to continuously shift and made them difficult to read. So for Part II of the study, Welsh Self-retaining Electrocardiogram Electrodes were used. See Figure 8. They remained fixed on the subject.

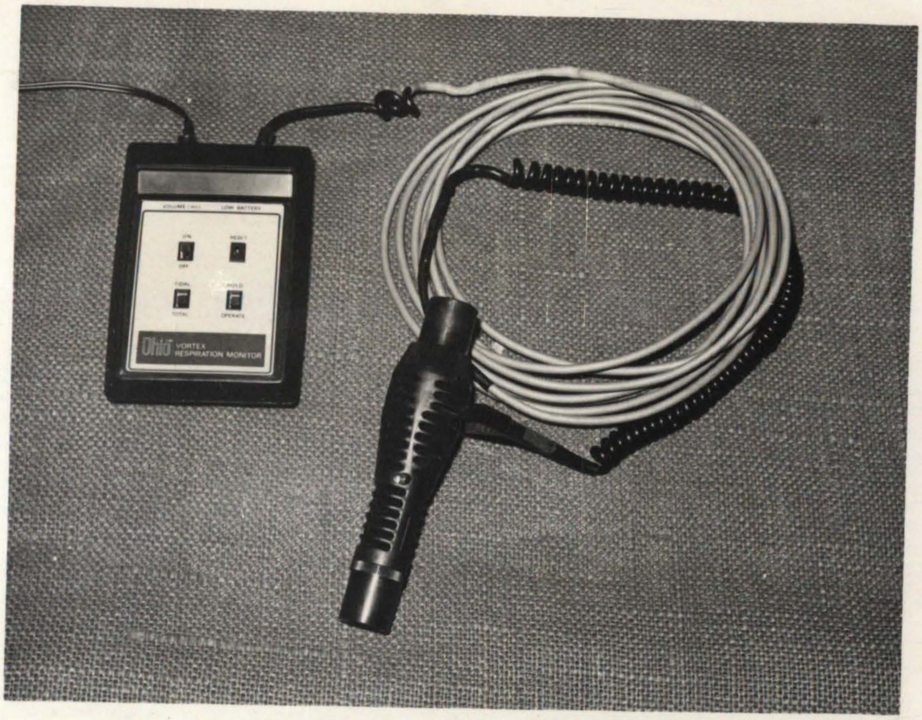

Figure 5. Ohio Vortex Respiration Monitor

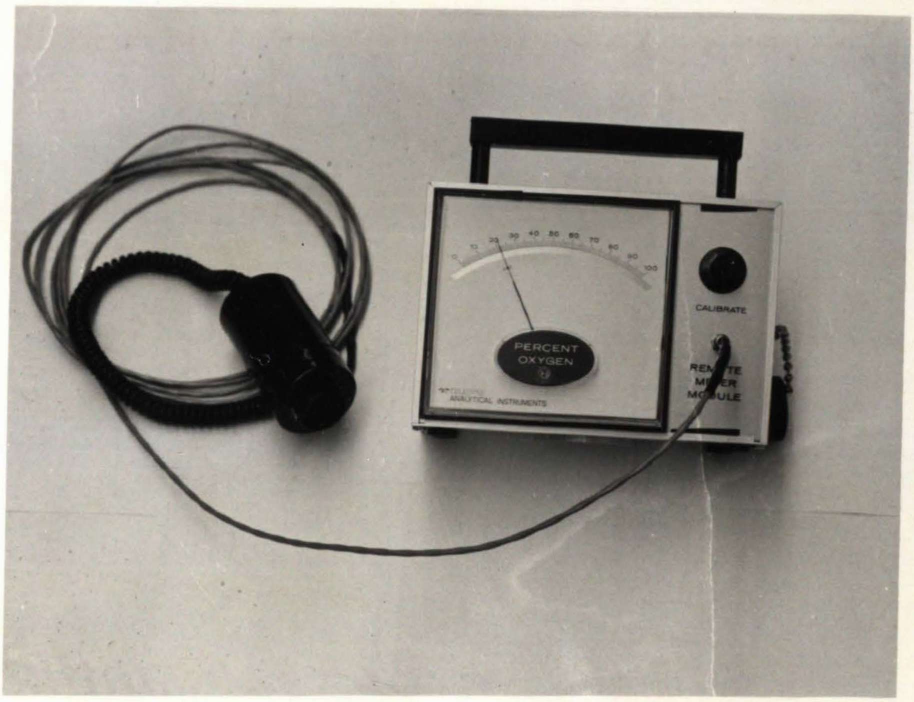

Figure 6. Teledyne Series 330 Portable Oxygen Monitor

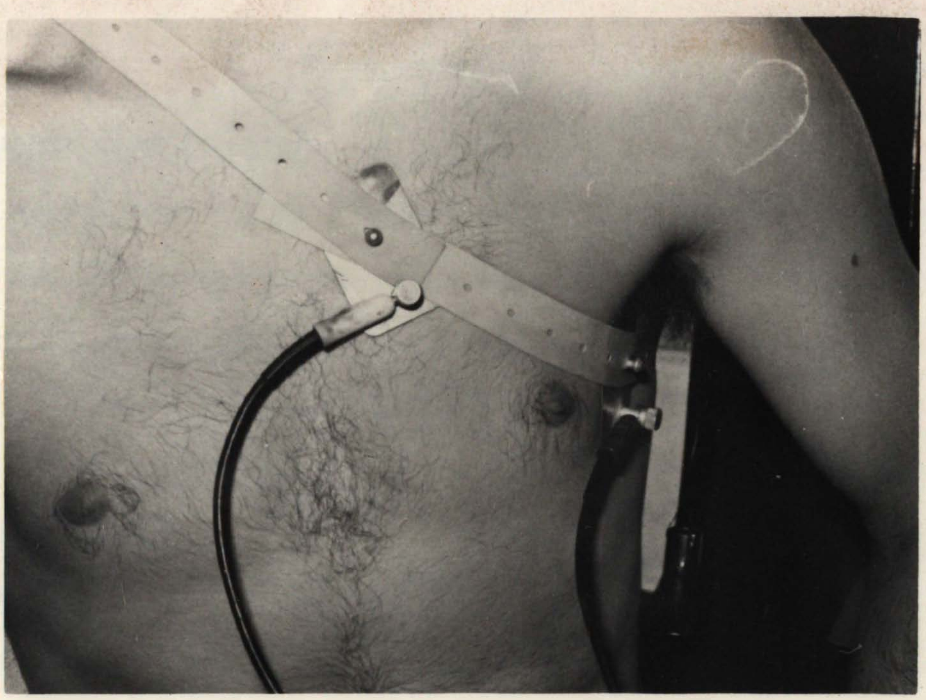

Figure 7. Flat Plate Electrodes Used For Electrocardiogram

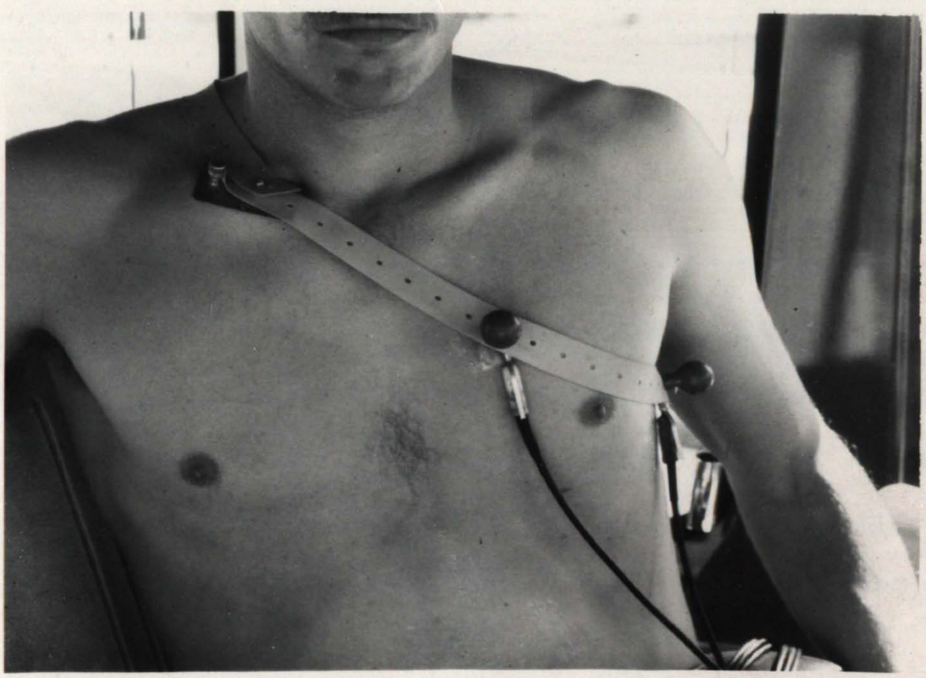

Figure 8. Welsh Electrodes Used For Electrocardiogram

Environmental Measurements

Environmental Test Facility

The environmental test facility designed by Turnquist et al. (31) was used for all of the tests. See Figure 9. The air distribution system inside the cab was designed to give an "air curtain" effect around the operator. High air velocities existed in the region outside of the operator's working area, while low air velocities existed around the operator.

Tests were conducted on the east side of the Agricultural Engineering building with the test facility facing south. Occasionally the test facility was left inside the building to simulate a very cloudy day where the mean radiant temperature equalled the dry-bulb air temperature. All tests were conducted in the morning. The first part of the study was conducted in July of 1975. The second part of the study was conducted during June and July of 1976.

Duct Air Flow Calibration

The duct which supplies air from the fan to the inlet plenum was probed to determine the air flow rate. The set-up was similar to Thomas (29). Velocity measurements at 12.7 mm increments across the duct were made using a Thermo-Systems 1051 series constant temperature hot wire anemometer. Then an IBM 360 computer was used to calculate incremental flow rates and sum these flow rates to obtain the total flow rate.

Thirteen fan speeds were used during the calibration process. The fan speeds ranged from 800 to 2000 RPM in increments of 100 RPM. Three

Figure 9. Environmental Test Facility

readings were taken at each fan speed. A linear regression analysis was made for flow rate in m^3/min versus fan speed in RPM. After calibration any desired air flow rate could be selected by setting the fan speed. Two calibrations were made because between the first and second parts of the study, a new air conditioning system was installed. The results are shown in Table 1.

TABLE 1

Regression Equations for Air Flow with Louvered Ceiling

Study No.	Regression Equation[1]	Variability Explained, R^2 (%)	Standard Deviation (m^3/min)
1	$m^3/\text{min} = 0.01048\,(\text{RPM}) - 1.205$	99.65	0.263
2	$m^3/\text{min} = 0.01039\,(\text{RPM}) - 1.938$	99.65	0.624

[1]Each equation is based on 13 points. The RPM range is from 800-2000.

In the first part of the study, three flow rates of 8.5, 12.5 and 16.5 m^3/min were used. In the second part, only the 8.5 m^3/min flow rate was used. This particular value was selected since it was similar to the air flow rate used by Eriksson and Domier (11).

Air Velocity Measurement

Measurements at two heights above the floor as suggested by Thomas (29) were taken to determine the relative air velocity. The lower level was 71.12 cm above the floor or just above the operator's knees. The upper level was 116.84 cm above the floor at approximately shoulder height of the operator. Velocity measurements were taken using a Thermo-Systems Model VT-161D omni-directional low velocity probe. A matrix was constructed around the operator's area. Readings were taken at 14 cm intervals starting at the rear left side of the operator and progressing in a clockwise direction. See Figure 10.

In addition:

1. The voltage output of the Thermo-Systems Model VT-161D velocity probe was recorded using one channel of a two channel oscillograph (Offner Type RS). The inking pen recorded dynamic data on curvilinear graph paper at 5 mm/sec with a sensitivity setting of 0.05 volts per line.

2. All velocity readings were taken with the cab in the east wing of the Agricultural Engineering building.

3. The velocity probe was hand held by the cab occupant for all readings.

4. Each data trace was then planimetered and the area compared to a known voltage per unit area to obtain a voltage output. This voltage was compared to the calibration curve to obtain an air velocity reading.

An average of all the velocity readings was used for the cab air velocity at each flow rate. The results are given in Table 2.

Figure 10. Cab Air Velocity Measurement

TABLE 2

Mean Air Velocities Inside Cab

Study No.	Flow Rate (m^3/min)	Air Velocity (m/min)	Standard Deviation (m/min)
1	8.5	10.39	6.16
1	12.5	17.22	9.88
1	16.5	28.03	13.62
2	8.5	11.45	6.67

Air velocity around the black globes was measured for determination of the mean radiant temperature. Velocity readings were taken on the four sides of a horizontal plane through the center of each of the black globes for each flow rate. The measurements were made using the low velocity probe (see Figure 11) and following the same procedure used for determining the cab air velocity. The results are shown in Table 3.

Figure 11. Black-Globe Air Velocity Measurement

TABLE 3

Air Velocities Around Black-Globes Inside Cab

		Upper Level[1]		Middle Level[2]		Lower Level[3]	
Study No.	Flow Rate (m^3/min)	Mean (m/min)	Standard Deviation (m/min)	Mean (m/min)	Standard Deviation (m/min)	Mean (m/min)	Standard Deviation (m/min)
1	8.5	7.74	3.20	8.34	0.94	3.73	1.44
1	12.5	12.80	1.43	14.55	2.39	13.41	4.20
1	16.5	20.31	2.83	22.97	4.35	18.33	2.53
2	8.5	10.08	1.25	18.03	0.80	12.78	2.00

[1] 121.9 cm above the floor.

[2] 76.2 cm above the floor.

[3] 20.3 cm above the floor.

Temperature Measurement

All temperature readings were made using 26 gauge copper-constantan thermocouples and a Honeywell 24 point strip-chart recording potentiometer. The mean cab temperature was determined by connecting 10 thermocouples in parallel. Thermocouples were located according to guidelines suggested by Hosler (14) and were shielded from the sun's radiation by a 6 cm length of 2 cm diameter plastic tubing covered with aluminum foil as shown in Figure 12. Wet-bulb temperatures were obtained using the temperature-humidity devices developed by Thomas (29).

Black-globe temperature sensors were made by inserting a thermocouple in a ping-pong ball which had been painted black. Black-globes

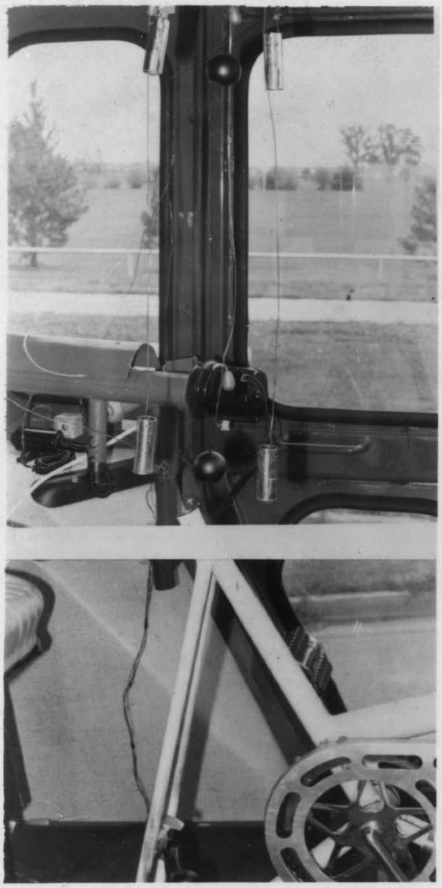

Figure 12. Shielded Thermocouples and Black-Globes

were hung at three heights, 20.3 cm, 76.2 cm and 121.9 cm above the floor. These heights are analogus to the heights of the thermocouples for determining mean cab temperature. See Figure 12.

Fourteen different temperature readings were taken inside and outside of the cab as defined in Table 4.

TABLE 4

Thermocouple Locations

Thermocouple No.[1]	Location
1	Mean cab temperature
2	Upper level black-globe temperature
3	Upper level air temperature
4	Middle level black-globe temperature
5	Middle level air temperature
6	Lower level black-globe temperature
7	Lower level air temperature
8	Return duct air temperature
9	Dry-bulb temperature inside cab
10	Wet-bulb temperature inside cab
11	Dry-bulb temperature outside cab
12	Wet-bulb temperature outside cab
13	Black-globe temperature outside cab
14	Air temperature outside cab

[1]Number corresponds to channel number of temperature recorder.

Data Collection Procedure

Tractor driving was simulated by pedalling a bicycle ergometer. The literature revealed no recent studies which had determined the energy expenditure necessary to drive a tractor for various farming operations. Domier (9) indicated need for research in this area. Astrand (3) reported that 4.0 Kcal/min was necessary to drive a tractor while plowing. This agreed reasonably well with 4.2 Kcal/min reported in the Biological Handbook on Metabolism (1). Yet, both values were considered high for today's tractors. An energy expenditure of 2.8 Kcal/min was selected for use in Part I of the study. This value is the energy required for driving a car. Subtracting the energy expenditure necessary for sitting at ease, 1.8 Kcal/min, reported in the Biological Handbook on Metabolism (1), resulted in a bicycle ergometer workload of 1.0 Kcal/min or 70 watts.

Part I

Upon arriving at the Agricultural Engineering building, the subject underwent several preparatory steps:

1. The subject was weighed while nude.
2. His height was measured.
3. His temperature was taken. Any subject with an above normal temperature was not allowed to participate.
4. Electrographic plates were fastened to the skin of the sternum and the left axillary region.

After these steps had been completed, the subject entered the cab and assumed a comfortable position in the operator's seat. Final instructions were given. The electrocardiographic leads and respiratory mask were attached. Final adjustments of the recorders were made. Temperatures were recorded while the subject was in the cab. The subject began pedalling when told to do so. During each pedalling bout, the workload was recorded. Since the metabolic rates or energy expenditure rates of the subject were obtained by measuring the oxygen consumption, it was critical that a steady state rate of oxygen consumption was attained. Webb (32) reported and McNall et al. (19) agreed that a man's metabolism and heart rate reach new plateaus within one to three minutes after he begins to work. After a preliminary test, the author decided that the subject should pedal two minutes before any readings were taken to assure that the subject's energy expenditure had reached a steady state value. After two minutes, the subject's heart rate was recorded. Likewise, three readings of the volume of the subject's pulmonary ventilation per minute and the percentage of oxygen in his expired air were taken. The subject was then allowed to stop while the cab air flow rate was changed. After this change, the subject started pedalling again and data was recorded.

The subject went through the same pedal-rest cycle for the three different air flow rates of 8.5, 12.5, and 16.5 m^3/min before the cab temperature was changed. When the cab temperature was changed, the respiration mask was removed and the subject was allowed to sit at ease in the cab. After the cab temperature had been changed, the respiratory mask was again attached and the subject began to pedal. Three cab temperatures of 18, 24, and 30° C were used.

Several changes were made between the first part and the second part of the study. After reviewing Part I of the study and obtaining additional information from Eriksson and Domier (11), it was decided that the original workload of 70 watts was too high. So, a new workload of 33 watts was used for Part II of the study. This workload agreed with the work of Eriksson and Domier (11). Results of Part I showed that the workload was significantly different from subject to subject. Workload varied because each subject pedalled at a slightly different speed. So for Part II, the tension on the bicycle ergometer was adjusted to compensate for the various pedalling rates. This resulted in a more uniform workload for all subjects.

Other minor changes were made between Part I and Part II of the study. Suction cups were used as electrodes for the electrocardiograms instead of flat plates. Also, an informed consent procedure was developed and used.

Part II

For Part II the preliminary procedures were similar to Part I. However, there was two exceptions. The subjects signed an informed consent procedure and went to the Student Health Service on the afternoon before their testing session for a complete physical examination. Otherwise all preparatory procedures were the same as in Part I.

The subject entered the cab next, assumed a comfortable position, and received final instructions. Recorder leads were attached as before, but the respiratory mask was not attached. The temperature recorder was started and the subject was allowed to adjust the thermostat in the cab. Adjustments were made until a comfortable cab temperature had been selected.

The subject alternatingly pedalled for five minutes and then rested for five minutes. Each half hour the subject's resting and pedalling heart rates were recorded. If the subject had been under a stressful condition his evaluation of comfort would have been in error. Heart rate was used as an indicator of stress since McNall et al. (20) established that the uniformity of pulse rate with time is an indicator that the subject was not under a stressful situation.

A man's idea of comfort may change with time. Rohles (27) did a study of comfort over a three hour period. He found that at the end of the first hour men were significantly warmer than at the end of the second hour, but they reported no significant change in their thermal sensations between the second and third hours. So the test was terminated after two hours. No thermal sensation votes were taken after this time since McNall (19) had pointed out that the use and annoyance of the metabolic equipment might influence the subject's comfort sensation. A respiratory mask was attached to the subject and he was asked to start pedalling again. The subject pedalled for five minutes, as before, and two readings of the volume of the subject's pulmonary ventilation per minute and the percentage of oxygen in his expired air were taken. The subject then rested for five minutes while two more readings were taken. Once more the subject was asked to pedal and then rest while readings were being taken. In this manner, eight separate metabolic readings--four resting and four pedalling--were obtained.

Chapter 4

PROCESSING THE DATA

Subject Characteristics

Sixteen males at South Dakota State University served as subjects in the first part of the study. Similarly, 16 male subjects participated in the second part of the study. Four subjects were involved in both sections. The subjects ranged in age from 21 to 25 years with a few exceptions. They ranged in height from 126 cm to 193 cm and in weight from 62.5 Kg to 101.2 Kg. All of the subjects serving in the study were caucasian. Tabulations of the physical characteristics of the subjects which are most pertinent to the study are provided in Table 5.

TABLE 5

Physical Characteristics of the Subjects

Subject	Age yrs.	Height cm	Weight kg	Surface Area M^2
		Part I		
1	24	177.8	78.9	1.97
2	22	184.8	76.7	2.00
3	23	180.0	75.9	1.95
4	23	182.9	76.0	1.98
5	25	181.6	77.1	1.98
6	23	183.8	74.2	1.96
7	23	188.9	75.5	2.02
8	25	192.7	85.5	2.16
9	22	191.1	77.6	2.06
10	23	181.0	85.0	2.06

Table 5 Continued

Subject	Age yrs.	Height cm	Weight kg	Surface Area M^2
11	23	179.1	73.9	1.92
12	24	176.2	73.9	1.90
13	36	172.7	79.2	1.93
14	24	161.9	62.5	1.66
15	22	188.3	84.6	2.11
16	33	179.7	93.6	2.13
		Part II		
1	21	185.4	77.6	2.01
2	24	188.0	76.1	2.02
3	23	182.6	92.8	2.15
4	34	180.3	101.2	2.21
5	22	185.4	80.7	2.05
6	24	181.0	74.6	1.94
7	24	175.9	70.3	1.86
8	23	179.1	63.0	1.80
9	24	178.4	73.8	1.92
10	24	182.2	82.1	2.04
11	28	182.2	74.6	1.96
12	25	168.3	78.2	1.88
13	24	185.4	72.6	1.96
14	23	175.3	65.2	1.80
15	19	175.6	68.0	1.83
16	27	179.7	90.0	2.10

Physiological Data

Pulmonary Ventilation

The measurements of the volumes of air inspired by each subject were obtained from the Ohio Vortex Respiration Monitor. These volumes were then corrected to the standard conditions (STPD) of temperature, 0^{o} C, and pressure, 760 mm dry. The correction factor was calculated from the following general equation (7):

$$CF = \frac{273}{T + 273} \times \frac{P_B - P_{H_2O}}{760}$$

where

CF = correction factor

T = ambient temperature, ^{o}C

P_B = ambient pressure, mm Hg

P_{H_2O} = water vapor tension at the ambient temperature, mm Hg

Mean cab temperature was used for the ambient temperature. Ambient pressure was obtained from the United States Weather Bureau Station located on top of the Agricultural Engineering building. Corrections for differences in elevation were considered unnecessary. Water vapor tension was calculated using Carrier's Equation.

The following calculation for pulmonary minute volume was then performed:

$$V_{STPD} = V_{observed} \times CF$$

where

V_{STPD} = Pulmonary Minute Volume corrected to STPD conditions, l/min

$V_{observed}$ = Pulmonary Minute Volume observed, l/min

CF = Correction Factor

Oxygen Consumption

The subject's oxygen consumption was determined as follows:

$$V_{O_2} = (0.209 - P_{O_2}) \times V_{STPD}$$

where

V_{O_2} = Oxygen Consumption, l/min

P_{O_2} = Percentage of oxygen in expired air, decimal

V_{STPD} = Pulmonary Minute Volume corrected to STPD conditions, l/min

The percentage of oxygen in the subject's expired air was read on the Teledyne Oxygen Analyzer. This percentage was then subtracted from 0.209, which is the percentage of oxygen in atmospheric air. The remainder represented the percentage of oxygen in the inspired air which had been consumed by the subject.

Metabolism

The calculation necessary to determine the subject's metabolic rate was as follows:

$$MR = \frac{V_{O_2} \times 4.825 \times 60}{A_{Du}}$$

where

MR = Metabolic Rate, $Kcal/m^2/hr$

V_{O_2} = Oxygen Consumption, l/min

A_{Du} = DuBois Body Surface Area, m^2

Metabolic rates were calculated assuming that the caloric value of oxygen was 4.825 kilocalories per liter. Adjustment was made for the body surface law by dividing by the DuBois body surface area. This law states that people under similar conditions give off the same quantity of heat per square meter of surface area (6). Thus, subjects of various sizes were equated to each other.

Heart Rate

Each electrocardiogram was labeled with the date of the test. The number of heart beats was determined by counting the number of tick marks on the electrocardiogram.

Environmental Data

Mean Radiant Temperature

A black-globe thermometer made of a ping-pong ball was used to determine the mean radiant temperature (MRT). The radiant exchange of the globe and its surroundings may be expressed by the following equation:

$$H_r = e\,\sigma\,(T_{MRT}^4 - T_g^{\,4})$$

and the convection exchange by the following equation:

$$H_c = h\sqrt{v}\,(t_g - t_a)$$

where

H_r = heat gain (or loss) by radiation, BTU/ft^2/hr

H_c = heat gain (or loss) by convection, BTU/ft^2/hr

t_g = temperature of globe, ^oF

t_a = temperature of air, ^oF

Tg = temperature of globe, ^oR

T_{MRT} = mean radiant temperature, ^oR

e = emissivity of globe surface, 0.95

σ = Stefan-Boltsman constant, 0.173×10^{-8} BTU/hr-ft^2-$^oR^4$

h = convection coefficient, BTU-min$^{1/2}$/hr-ft$^{5/2}$-^oF

v = air velocity, fpm

Pereira *et al.* (25) determined a value representing a convective coefficient for a ping-pong ball black-globe thermometer with an emissivity of the globe surface of 0.98 by comparing the ball and a 6 inch copper black-globe thermometer exposed together in the sun. From a series of 91 observations the following radiant heat load (RHL) equation was developed:

$$RHL = 0.232 \sqrt{v}\,(t_g - t_a) + \sigma\, Tg^4$$

Bond and Kelley (4) observed that the radiant heat load is the total radiation received by an object from all of the surrounding space. The definition says nothing about the net exchange of radiation between the object and its surrounding envelope. Expressed mathematically:

$$RHL = \sigma\, T_{MRT}^4$$

Solving the above equations, the convective coefficent for a ping-pong ball is 0.22736.

Under steady state conditions, the effects of radiation and convection balance each other. Hence, the radiation and convection equations can be equated and solved to give the MRT:

$$T_{MRT}^4 = Tg^4 + (1.383 \times 10^8)\sqrt{v}\,(t_g - t_a)$$

So by measuring the air velocity with a hot wire anemometer, and recording the black-globe temperatures and air temperatures with the temperature recorder, it was possible to determine the mean radiant temperature.

Pressure of Water Vapor in Ambient Air

The Carrier Equation presented by Faires (12) was used to determine the partial pressure of the vapor for ordinary atmospheric air. The equation is as follows:

$$P_v = P_{VWB} - \frac{(P-P_{VWB})\,(t_{db}-t_{wb})}{2830 - 1.44\,t_{wb}}$$

where

P_v = vapor pressure of the superheated vapor, psia

P_{VWB} = vapor pressure at the wet bulb temperature, psia

P = barometric pressure, psia

t_{db} = dry-bulb temperature, ^oF

t_{wb} = wet-bulb temperature, ^oF

This equation was solved using the IBM 360 computer. Values for P_{VWB} were taken from Table 7-2 of Olivieri (24).

Predicted Mean Vote

With the comfort equation as a starting point, Fanger (13) derived an index which makes possible a prediction of the thermal sensation for any given combination of activity level, clo-value, and four thermal environmental parameters. The index was based on a scale from -3 to +3 with 0 being the comfortable condition. A positive value corresponded to the warm side of neutral and a negative vote to the cold side of neutral. The thermal sensation index is referred to as the Predicted Mean Vote (PMV) and is as follows:

$$PMV = (0.352e^{-0.042(M/A_{Du})} + 0.032) \left[\frac{M}{A_{Du}} (1-\eta) - \right.$$

$$0.35\ [43-0.061 \frac{M}{A_{Du}} (1-\eta) - Pa] -$$

$$0.42\ [\frac{M}{A_{Du}} (1-\eta) - 50] -$$

$$0.0023 \frac{M}{A_{Du}} (44-Pa) - 0.0014 \frac{M}{A_{Du}} (34-ta) -$$

$$3.4 \times 10^{-8} f_{cl}\ [(t_{cl}+273)^4-(t_{mrt}+273)^4]$$

$$\left. - f_{cl}h_c\ (t_{cl}-ta)\right]$$

where t_{cl} is determined by the equation

$$t_{cl} = 35.7 - 0.032 \frac{M}{A_{Du}} (1-\eta) -$$

$$0.18\ I_{cl} \left[3.4 \times 10^{-8} f_{cl}\ [(t_{cl}+273)^4 - \right.$$

$$\left.(t_{mrt}+273)^4] + f_{cl}h_c(t_{cl}-t_a)\right]$$

and h_c by

$$h_c = \begin{cases} 2.05\ (t_{cl}-t_a)^{0.25} & \text{for } 2.05\ (t_{cl}-t_a)^{0.25} > 10.4 \sqrt{v} \\ 10.4 \sqrt{v} & \text{for } 2.05\ (t_{cl}-t_a)^{0.25} < 10.4 \sqrt{v} \end{cases}$$

Solution of the PMV was programmed on the IBM 360 computer. All of the inputs into the PMV equation were measured during the testing session except for the thermal resistance of the clothing (I_{cl}) and the ratio of the surface area of the clothed body to the nude body (f_{cl}). These values were taken from Table 2, Data for Different Clothing Ensembles, of Fanger (13), assuming the subjects were wearing a light summer clothing ensemble. It was also assumed that the mechanical efficiency (η) of pedalling the bicycle ergometer was zero. The equation was solved for the PMV of each subject at one-half hour intervals. This data was then analyzed to determine if Fanger's thermal sensation index was valid for a tractor cab environment.

Chapter 5

RESULTS AND CONCLUSIONS

Part I

Workload

Analysis of variance on the workload revealed that it was not constant from individual to individual as shown in Table 6.

TABLE 6

Analysis of Variance, Levels of Work Performed

Source	df	Sum of Squares	Mean Squares	F
Total	144	29948922.00		
Individuals	15	194128.67	12941.91	8.710 **
Remainder	128	190199.56	1485.93	

**Significant at 1% level.

However, the literature reveals that "oxygen uptake increases roughly linearly with an increase in work load" (3). Furthermore, "there is generally a linear relationship between O_2 uptake and heart rate" (3). Similarly, pulmonary ventilation rises in a linear relationship to oxygen uptake for the range of workloads used (3). Therefore, it was decided in analyzing future variables, work would be fit as a continuous variable simultaneously with the other factors.

Heart Rate

Analysis of variance for the heart rate of the cab occupants is shown in Table 7. The linear effect of work explained a significant amount (1% level) of the variability in heart rate. Temperature had a significant effect at the 5% level on heart rate. Air velocity didn't influence heart rate and there were no interaction effects.

TABLE 7

Analysis of Variance, Heart Rate of the Occupants

Source	df	Sum of Squares	Mean Squares
Individuals	15	33243.05	2216.20
Temperature	2	891.54	445.77
Individuals x temperature	29	3488.24	120.28
Velocity	2	11.46	5.73
Individuals x velocity	30	987.95	32.93
Temperature x velocity	4	25.16	6.29
Individuals x temperature x velocity	57	1799.73	31.57
Work	1	368.96	368.96
Remainder	271	2678.39	9.88

Mean values of the heart rates are presented in Table 8. Increasing temperature had a significant effect at the 5% level of raising the heart rates. As the cab temperature was raised from 19.2° C to 29.9° C the heart rates were increased 3%. Air velocity had no significant effect on heart rates.

TABLE 8

Mean Values, Heart Rate (Beats/min)

Cab Temperature	Cab Air Velocity, m/min 10.39	17.22	28.03	Temperature Level Means
19.2° C	109.7	108.5	109.4	109.2
23.9° C	109.5	109.4	109.2	109.4
29.9° C	112.6	112.6	112.6	112.6
Velocity level means	110.6	110.2	110.4	

Overall mean = 110.4

Pulmonary Ventilation

Analysis of variance for the pulmonary ventilation of the cab occupants is shown in Table 9. Again the linear effect of work explained a significant amount (1% level) of the variability in pulmonary ventilation, but there were no significant differences in ventilation due to temperature or velocity changes. Also, no interactions were present.

TABLE 9

Analysis of Variance, Pulmonary Ventilation of the Occupants

Source	df	Sum of Squares	Mean Squares
Individuals	15	15176.34	1011.76
Temperature	2	21.46	10.73
Individuals x temperature	30	1396.65	46.56
Velocity	2	2.71	1.36
Individuals x velocity	30	205.84	6.86
Temperature x velocity	4	11.66	2.92
Individuals x temperature x velocity	60	644.23	10.74
Work	1	32.53	32.53
Remainder	287	440.34	1.53

Mean values for pulmonary ventilation are featured in Table 10. No factors of interest were significantly different.

TABLE 10

Mean Values, Pulmonary Ventilation (l/min)

Cab Temperature	Cab Air Velocity, m/min 10.39	17.22	28.03	Temperature Level Means
19.2° C	21.2	20.7	21.4	21.1
23.9° C	21.6	21.5	21.4	21.5
29.9° C	20.9	21.0	20.9	20.9
Velocity level means	21.2	21.1	21.2	

Overall mean = 21.19

Oxygen Consumption

Analysis of variance for the oxygen consumption of the cab occupants is shown in Table 11. Once more, the linear effect of work explained a significant amount (1% level) of the variability in oxygen consumption. There was a significant difference of oxygen consumption at the 1% level between temperatures, but velocity effects and interactions were nonsignificant.

TABLE 11

Analysis of Variance, Oxygen Consumption of the Occupants

Source	df	Sum of Squares	Mean Squares
Individuals	15	72.11	4.81
Temperature	2	5.35	2.67
Individuals x temperature	30	6.80	0.23
Velocity	2	0.01	0.005
Individuals x velocity	30	0.80	0.03
Temperature x velocity	4	0.10	0.02
Individuals x temperature x velocity	60	2.20	0.04
Work	1	0.21	0.21
Remainder	287	2.18	0.008

Mean values of oxygen consumption are exhibited in Table 12. Increasing air temperature enhanced the oxygen consumption significantly (1% level). As air temperature rose from 19.2° C to 29.9° C the oxygen consumption increased 23%.

TABLE 12

Mean Values, Oxygen Consumption (1/min)

Cab Temperature	Cab Air Velocity, m/min 10.39	17.22	28.03	Temperature Level Means
19.2° C	1.12	1.16	1.15	1.14
23.9° C	1.31	1.28	1.25	1.28
29.9° C	1.42	1.42	1.42	1.42
Velocity level means	1.28	1.29	1.27	

Overall mean = 1.28

Metabolic Rate

Analysis of variance of the metabolic rate of the cab occupants is shown in Table 13. As before, the linear effect of work explained a significant amount (1% level) of the variability in metabolic rate. Temperature had a significant effect at the 1% level on metabolism but air velocity didn't effect it. Also, there were no interactions present.

TABLE 13

Analysis of Variance, Metabolic Rate of the Occupants

Source	df	Sum of Squares	Mean Squares
Individuals	15	1455930.06	97062.00
Temperature	2	112234.95	56117.47
Individuals x temperature	30	147389.77	4912.99
Velocity	2	505.67	252.83
Individuals x velocity	30	17537.39	584.58
Temperature x velocity	4	1989.99	497.50
Individuals x temperature x velocity	60	43724.21	728.74
Work	1	5268.69	5268.69
Remainder	287	37673.34	131.27

Mean values of the metabolic rates are displayed in Table 14. Increasing air temperature significantly elevated the metabolic rate at the 1% level. As the temperature rose from 19.2^{o} to 29.9^{o} C, the metabolic rate was enhanced 23%, parallel to the enhanced oxygen consumption.

TABLE 14

Mean Values, Metabolic Rate (Kcal/m^2/hr)

Cab Temperature	Cab Air Velocity, m/min 10.39	17.22	28.03	Temperature Level Means
19.2° C	162.5	168.4	166.2	165.7
23.9° C	189.9	187.8	181.8	186.5
29.9° C	205.8	206.3	206.4	206.2
Velocity level means	186.1	187.5	184.8	

Overall mean = 186.14

Conclusions

A statistical summary is given in Table 15.

TABLE 15

Statistical Summary

Parameter	Heart Rate	Pulmonary Ventilation	Oxygen Consumption	Metabolic Rate
Temperature	*	ns	**	**
Velocity	ns	ns	ns	ns
Temperature x velocity	ns	ns	ns	ns
Work linear	**	**	**	**

ns Non-significant.

* Significant at 5% level.

** Significant at 1% level.

Conclusions from Part I of the study are as follows:

1. Increasing cab air temperature had an effect of significantly elevating heart rate at the 5% level and significantly raising oxygen consumption and metabolic rate at the 1% level, but did not have any significant effects on pulmonary ventilation.

A physiological explanation for these results may be hypothesized. A cab temperature of 23.9^{o} C is assumed as a normal operating temperature. Then, elevating or lowering the cab temperature may influence the subject's autonomic nervous system. Since the subject was at a particular cab air temperature-velocity combination for only about six minutes, it was assumed for most of the subjects studied that this time period did not allow for notable physiological changes by the subject's endocrine system components.

The sympathetic part of the autonomic nervous system becomes dominant in response to elevated cab temperature. It promotes increased venous return to the heart which enhances blood pressure, heart rate and peripheral vasodialation to dissipate body heat, mainly by radiation. Some heat loss is also accomplished by evaporation. Stress on the subject caused by difficulty to adequately dissipate body heat increases oxygen consumption and metabolic rate with resulting elevation of carbon dioxide pressure and hydrogen ion concentration in the cardiovascular system. These responses stimulate chemoreceptors in the carotid sinus and aortic bodies which enhance pulmonary ventilation and heart rate to compensate primarily for hypercapnia, relative hypoxia and metabolic acidosis.

Lowering the cab temperature causes a subjective response of increasing comfort. The subject is in a pleasant environment relative to the outside summer conditions. The subjects feel comfortable because of the enhanced heat dissipation, mainly by radiation. The parasympathetic system of the autonomic nervous system becomes functional. Calmness, reduced oxygen consumption and diminished metabolic rate ensue in the subject. These responses do not stimulate chemoreceptors thereby allowing reduced pulmonary ventilation and heart rate.

2. Cab air velocities did not have any significant statistical effects.

The effect of cab air velocity on physiological parameters may be hypothesized. Increasing cab air velocities at 19.2° C resulted in some body heat loss by conduction and convection. Attempting to conserve body heat, the peripheral blood vessels were constricted through the sympathetic vasconstrictor nerves innervating the subcutaneous skin vessels. Heart rate, pulmonary ventilation, oxygen consumption and metabolic heat production would then be elevated to counteract body heat loss.

Increasing cab air velocities at 23.9° and 29.9° C promoted body heat dissipation in the subject. The peripheral blood vessels dialated thereby increasing heat transfer from the body core areas to the peripheral shell of the body for heat dissipation utilizing conduction and convection with higher cab air velocities. The elevated body heat loss would result in lowered pulmonary ventilation, oxygen consumption, metabolic rate and heart rate.

Part II

Predicted Mean Vote

Predicted mean votes for each subject are delineated in Table 16.

TABLE 16

Predicted Mean Votes of Tractor Cab Occupants

Subject	Time, Hours 0.5	1.0	1.5	2.0
1	-0.35	-0.39	-0.22	-0.49
2	-0.44	-0.48	-0.33	-0.45
3	0.42	0.18	0.19	0.28
4	-0.59	-0.43	-0.34	-0.34
5	0.27	0.35	0.32	0.32
6	0.96	1.07	0.70	0.76
7	0.78	0.74	0.78	0.72
8	-1.00	-1.24	-1.16	-1.25
9	0.04	0.12	0.19	0.35
10	0.03	0.04	-0.06	-0.04
11	0.51	0.53	0.45	0.42
12	0.66	0.46	0.31	0.12
13	1.15	0.42	0.22	0.59

Table 16 Continued

	Time, Hours			
Subject	0.5	1.0	1.5	2.0
14	0.26	0.43	0.04	0.24
15	-0.27	-0.24	-0.47	-0.71
16	0.56	-0.13	-0.21	-0.30
Mean	0.19	0.10	0.03	0.02

Analysis of variance of the predicted mean vote (PMV) is shown in Table 17. A highly significant difference of the PMV among individuals is noted, which emphasizes the fact that people differ in their perception of comfort. However, the PMV was not meant to be used individually but rather as "an expression for the general degree of discomfort for the group as a whole" (13). Effects of time will be discussed later in the text.

TABLE 17

Analysis of Variance, Predicted Mean Vote

Source	df	Sum of Squares	Mean Squares	F
Total	64	19.80		
Time	3	0.30	0.10	3.318 *
Individuals	15	17.69	1.18	39.358 **
Remainder	45	1.38	0.03	

* Significant at 5% level.

** Significant at 1% level.

Analysis of variance of the cab temperature selected by the occupants is shown in Table 18. Highly significantly different cab temperatures were selected by the subjects in order to be comfortable. This suggests that people have differing sensations of comfort. It also implies that the operator should be able to vary the cab temperature.

TABLE 18

Analysis of Variance, Cab Temperature Selected

Source	df	Sum of Squares	Mean Squares	F
Total	64	28423.37		
Time	3	4.13	1.38	2.210 ns
Individuals	15	104.20	6.95	11.160 **
Remainder	45	28.01	0.62	

ns Non-significant.

** Significant at 1% level.

Referring to Table 18, the cab temperature selected by an individual did not change significantly with time. In contrast, the PMV was indicated in Table 17 to change significantly with time. This would suggest that cab temperature alone is not sufficient for predicting comfort if Fanger's equation for PMV applies to tractor cabs. Other conditions such as mean radiant temperature, air velocity, air humidity, clothing and activity level must also be considered.

Time Effect

The theory that the concept of comfort may change with time was proposed by Rohles (27) and was the basis for conducting the tests for two hours. The means of the PMV's of all subjects are shown in Table 16. The PMV decreases with time and then stabilizes. Three orthogonal comparisons are presented in Table 19. Comparisons were made to determine if and when the PMV stabilized with respect to time. The results showed that the reading at the first half hour differed significantly from the other comfort readings.

TABLE 19

Orthogonal Comparisons of Predicted Mean Votes with Respect to Time

Time	Sum of Squares	Mean Squares	F
1 vs. 2 + 3 + 4	0.2465	0.2465	8.228 **
2 vs. 3 + 4	0.0504	0.0504	1.682 ns
3 vs. 4	0.0013	0.0013	0.043 ns

ns Non-significant.

** Significant at 1% level.

1 PMV at end of 0.5 hour.

2 PMV at end of 1 hour.

3 PMV at end of 1.5 hours.

4 PMV at end of 2 hours.

Test Hypothesis

The primary objective of Part II of the study was to determine the applicability of Fanger's concepts. The subjects were allowed to adjust the cab temperature until they were comfortable. Hence, the mean of the PMV's from the individuals should equal zero if Fanger's theory applied. This hypothesis was tested using a t-test. See Table 20.

The final three readings of the PMV from each subject were used in the test since they did not differ significantly. Results showed that the mean of the PMV's did equal zero. Therefore, Fanger's equation for PMV can be used to predict comfort in a tractor cab for summer conditions in South Dakota.

TABLE 20

Hypothesis Test

Comparison	Test Statistic	Test Statistic Value
$\mu = \mu_o$	$t = \dfrac{\bar{x} - \mu_o}{s/\sqrt{n-1}}$	0.559 ns

ns Non-significant.

μ Mean of Test Population.

μ_o Theoretical Mean of PMV's (equal to zero).

Conclusions

Conclusions from Part II of the study are as follows:

1. Fanger's equation for Predicted Mean Vote did adequately predict comfort in a tractor cab for summer conditions in South Dakota.

2. A person's idea of comfort changed during the first half-hour after entering the tractor cab and then remained steady for the rest of the time spent in the tractor cab.

3. Cab air temperature alone is not a sufficient indicator of comfort in a tractor cab. Since Fanger's equation for Predicted Mean

Vote applies, other factors such as mean radiant temperature, air velocity, air humidity, clothing and activity level need to be considered for predicting comfort.

4. Cab air temperature, cab air velocity, and clothing worn are parameters which may be most easily varied to adjust for changing sensations of comfort.

Chapter 6

SUMMARY

Part I

This was a study of the influence of ambient temperature and air velocity on human beings while performing a 70 watt workload in a tractor cab. Sixteen male university student subjects were exposed to ambient temperatures of 19.2^{o}, 23.9^{o} and 29.9^{o} C and to air flow rates of 10.39, 17.22 and 28.03 m/min. The workload generated by pedalling a bicycle ergometer was similar to that necessary to operate a tractor-mounted front-end loader. Data was collected and analyzed to determine if air temperature and velocity effected physiological responses.

Increasing cab air temperature had a significant effect of elevating heart rate, oxygen consumption and metabolic rate. Pulmonary ventilation was non-significant under these experimental conditions.

Air velocity showed no significant effects.

Part II

This study was done to determine the applicability of Fanger's concepts of comfort to a tractor cab occupant. Sixteen male university student subjects were exposed to an air flow rate of 8.5 m^3/min and a mean cab air velocity of 11.45 m/min. They pedalled against a workload of 33 watts on a bicycle ergometer for five minutes with five minute rest intervals and were allowed to adjust the cab temperature to maintain a comfortable environment. Each subject remained in the cab for two hours. Pertinent data necessary to determine comfort was measured each half hour. Predicted mean votes were calculated from the data collected for each subject and were analyzed.

It was concluded that Fanger's equation for Predicted Mean Vote did adequately predict comfort in a tractor cab for summer conditions in South Dakota. Also, a person's idea of comfort did not change significantly after the first half-hour in the tractor cab. Finally, cab temperature alone is not an adequate indicator of comfort in a tractor cab.

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APPENDIX A

SUMMARY OF CALCULATIONS

The following example illustrates the treatment of the data by means of a sequence of formulas used in the study.

1. Subject: number one

   Height: 185.4 cm

   Weight: 77.6 Kg

   Age: 21

   Body Surface Area (A_{Du}): 2.01 m^2

2. Workload = Tension (kiloponds) x Speed (Rev/sec)

   x 1.625 meters/rev x 60 sec/min

   = 0.69 x 3.0 x 1.625 x 60

   = 202 kilopond-meters/min

   = 33 watts

3. Ambient Temperature (T or t_a) = 18.3^o C

4. Dry-bulb Temperature (t_{db}) = 19.2^o C = 66.6^o F

5. Wet-bulb Temperature (t_{wb}) = 13.1^o C = 55.6^o F

6. Barometric Pressure (P) = 13.77 psia

   Ambient Pressure (P_B) = 714 mm Hg

7. Vapor Pressure at the Wet-bulb Temperature (P_{vwb})

   = 0.21792 psia [from Table 7-2 of Olivieri (24)]

8. Pressure of Water Vapor in Ambient Air (P_v)

$$= P_{vwb} - \frac{(P-P_{vwb})\ (t_{db}-t_{wb})}{2830 - 1.44\ t_{wb}}$$

$$= 0.21792 - \frac{(13.77-0.21792)\ (66.6-55.6)}{2830 - 1.44\ (55.6)}$$

   = 0.164 psia

Water Vapor Tension at the Ambient Temperature (P_{H_2O} or P_a)

= 8.48 mm Hg

9. Correction Factor (CF)

$$= \frac{273}{T + 273} \times \frac{P_B - P_{H_2O}}{760}$$

$$= \frac{273}{18.3 + 273} \times \frac{714 - 8.48}{760}$$

= 0.870

10. Pulmonary Ventilation (V_{STPD})

= $V_{observed} \times CF$

= 18.95 x 0.870

= 16.49 Liters/min

11. Oxygen Consumption (V_{O_2})

= $(0.209 - P_{O_2}) \times V_{STPD}$

= (0.209 - 0.155) x 16.49

= 0.907 Liters/min

12. Metabolic Rate (MR)

$$= \frac{V_{O_2} \times 4.825 \times 60}{A_{Du}}$$

$$= \frac{0.907 \times 4.825 \times 60}{2.01}$$

= 130.4 $Kcal/m^2$-hr

13. Mean Radiant Temperature (t_{MRT}):

Black-globe Temperature (t_g) = 67.5^o F

Ambient Air Temperature (t_a) = 62.5^o F

Air Velocity (v) = 10.08 m/min = 33.1 fpm

$$T^4_{MRT} = T^4_g + (1.383 \times 10^8)\ \sqrt{v}\ (t_g - t_a)$$

$$= (67.5 + 460)^4 + (1.383 \times 10^8)\ \sqrt{33.1}\ (67.5 - 62.5)$$

$t_{MRT} = 74.1^{\circ}$ F $= 23.4^{\circ}$ C

14. Predicted Mean Vote (PMV):

Activity level (M/A_{Du}) = 78.7 Kcal/hr-m^2 (Average of 8 readings)

Clothing: $\left.\begin{array}{l} f_{cl} = 1.11 \\ I_{cl} = 0.50 \end{array}\right\}$ From Table 2 of Fanger (13)

Air Temperature (t_a) = 18.3° C

Mean Radiant Temperature (t_{MRT}) = 22.7° C (Average of 3 readings)

Relative Air Velocity (v) = 0.10 m/sec

Air Humidity (p_a) = 8.48 mm Hg

Using the above variables, the equations on page 47 of the text were solved with an IBM 360 computer to present the following results:

t_{cl} = 27.86° C

PMV = -0.49

APPENDIX B

EXPERIMENTAL DATA

Subject	Air Temperature °C	Air Velocity m/min	Ventilation Rate l/min			Oxygen consumption l/min			Metabolic Rate $Kcal/m^2/hr$			Heart Rate Beats/min		
1	19.2	10.39	21.36	23.12	23.37	1.17	1.15	1.17	172.17	169.22	172.17	99	102	100
1	19.2	17.22	24.83	23.47	24.72	1.49	1.17	1.36	219.25	172.17	200.12	100	99	100
1	19.2	28.03	25.73	25.36	24.20	1.29	1.27	1.21	189.82	186.88	178.05	102	102	100
1	23.9	10.39	23.64	25.17	25.08	1.42	1.38	1.25	208.95	203.07	183.94	98	104	99
1	23.9	17.22	24.10	24.23	25.61	1.21	1.21	1.28	178.05	178.05	188.35	99	96	99
1	23.9	28.03	23.64	24.55	24.04	1.18	1.23	1.20	173.64	181.00	176.58	96	96	102
1	29.9	10.39	24.93	25.61	26.05	1.62	1.53	1.56	238.38	225.14	229.55	100	106	104
1	29.9	17.22	23.57	25.16	25.11	1.54	1.64	1.51	226.61	239.86	222.20	104	102	105
1	29.9	28.03	24.07	19.37	18.45	1.69	1.35	1.11	248.68	198.65	163.34	104	108	105
2	19.2	10.39	21.56	17.69	19.37	1.19	0.89	0.97	172.41	128.94	140.53	108	108	111
2	19.2	17.22	16.62	14.69	14.90	0.84	0.74	0.75	121.70	107.21	108.66	104	100	110
2	19.2	28.03	23.35	24.26	24.89	1.17	1.21	1.24	169.51	175.31	179.65	108	111	108
2	23.9	10.39	21.19	19.94	23.04	1.27	1.20	1.16	184.00	173.86	168.06	105	106	111
2	23.9	17.22	18.04	19.97	17.68	1.08	1.20	0.97	156.47	173.86	140.53	102	104	105
2	23.9	28.03	15.19	17.57	19.69	0.76	0.88	0.98	109.88	127.10	142.49	100	104	111
2	29.9	10.39	24.19	19.84	20.78	1.70	1.39	1.45	246.30	201.38	210.08	104	108	112
2	29.9	17.22	25.17	24.08	26.66	1.77	1.69	1.87	256.44	244.85	270.93	106	112	116
2	29.9	28.03	29.43	30.45	26.36	2.06	2.13	1.84	298.45	308.60	266.58	116	120	118
3	19.2	10.39	23.86	25.44	26.09	1.20	1.28	1.18	177.97	189.83	175.00	114	120	122
3	19.2	17.22	22.44	24.72	24.11	1.35	1.36	1.21	200.21	201.69	179.45	114	112	117
3	19.2	28.03	25.54	26.56	26.03	1.28	1.20	1.17	189.83	177.97	173.52	120	120	120
3	23.9	10.39	23.62	23.86	25.63	1.30	1.20	1.28	192.80	177.97	189.83	120	120	126
3	23.9	17.22	20.32	23.36	24.28	1.32	1.40	1.45	195.76	207.63	215.04	117	123	123
3	23.9	28.03	24.44	26.30	26.13	1.22	1.31	1.31	180.93	194.28	194.28	124	124	116
3	29.9	10.39	21.89	23.65	24.56	1.42	1.53	1.47	210.59	226.91	218.01	110	112	120

Subject	Air Temperature °C	Air Velocity m/min	Ventilation Rate l/min			Oxygen Consumption l/min			Metabolic Rate Kcal/m^2/hr			Heart Rate Beats/min		
3	29.9	17.22	24.89	27.09	27.58	1.75	1.77	1.80	259.53	262.50	266.95	124	123	123
3	29.9	28.03	25.81	25.99	26.83	1.68	1.81	1.74	249.15	268.43	258.05	122	122	124
4	19.2	10.39	24.16	26.18	28.05	1.21	1.04	1.13	177.30	152.39	165.58	104	104	108
4	19.2	17.22	23.19	24.24	24.09	1.16	1.09	0.97	169.97	159.71	142.13	105	102	104
4	19.2	28.03	24.85	27.96	26.02	1.37	1.40	1.30	200.74	205.14	190.49	108	108	111
4	23.9	10.39	24.98	24.33	26.01	1.50	1.46	1.56	219.79	213.93	228.58	102	104	104
4	23.9	17.22	24.70	23.67	23.17	1.48	1.42	1.39	216.86	208.07	203.67	100	104	104
4	23.9	28.03	22.51	22.67	23.36	1.35	1.36	1.40	197.81	199.28	205.14	102	102	104
4	29.9	10.39	25.34	26.19	25.22	1.78	1.83	1.64	260.82	268.15	240.31	104	110	104
4	29.9	17.22	25.79	26.31	24.93	1.81	1.84	1.75	265.81	269.61	256.42	105	108	108
4	29.9	28.03	26.41	24.23	25.68	1.72	1.70	1.80	252.03	249.10	263.75	114	104	110
5	19.2	10.39	33.24	37.14	36.12	1.66	1.67	1.45	242.93	244.40	212.20	140	147	144
5	19.2	17.22	24.49	27.55	35.29	1.47	1.38	1.41	215.13	201.96	206.35	135	136	141
5	19.2	28.03	36.26	35.85	35.39	1.63	1.44	1.42	238.54	210.74	207.81	150	144	144
5	23.9	10.39	25.64	26.73	26.77	1.54	1.47	1.47	225.37	215.13	215.13	112	114	117
5	23.9	17.22	27.05	26.05	28.94	1.49	1.31	1.59	218.05	191.71	232.69	116	120	120
5	23.9	10.39	24.46	24.75	25.54	1.47	1.48	1.53	215.13	216.59	223.91	108	114	111
5	29.9	10.39	22.06	23.94	26.52	1.43	1.43	1.59	209.27	209.27	232.69	124	130	129
5	29.9	17.22	21.18	23.34	28.29	1.38	1.40	1.69	201.96	204.88	247.32	129	132	134
5	29.9	28.03	24.18	16.41	17.93	1.57	1.06	1.07	229.76	155.13	156.59	128	132	136
6	19.2	10.39	27.99	26.95	27.84	1.40	1.22	1.26	206.48	179.93	185.83	108	105	108
6	19.2	17.22	24.55	24.86	25.10	1.48	1.49	1.38	218.28	219.75	203.53	104	105	105
6	19.2	28.03	25.80	26.89	27.45	1.29	1.35	1.38	190.25	199.10	203.53	105	108	108
6	23.9	10.39	27.82	27.12	30.01	1.81	1.76	1.80	266.95	259.57	265.47	120	120	120
6	23.9	17.22	27.53	27.52	24.85	1.65	1.65	1.50	243.35	243.34	221.23	116	117	112
6	23.9	28.03	24.56	24.53	26.29	1.72	1.59	1.58	253.67	234.50	233.02	123	120	120
6	29.9	10.39	23.62	22.65	24.86	1.65	1.59	1.62	243.35	234.50	238.92	124	120	128

Subject	Air Temperature °C	Air Velocity m/min	Ventilation Rate l/min			Oxygen Consumption l/min			Metabolic Rate Kcal/m^2/hr			Heart Rate Beats/min		
6	29.9	17.22	19.98	20.77	21.98	1.40	1.35	1.42	206.48	199.10	209.43	108	108	111
6	29.9	28.03	24.46	24.15	25.53	1.72	1.69	1.79	253.67	249.25	264.00	120	124	123
7	19.2	10.39	13.07	13.07	13.90	0.79	0.79	0.84	113.35	113.35	120.53	99	100	98
7	19.2	17.22	13.20	15.43	15.38	0.80	0.85	0.85	114.79	121.96	121.96	99	102	100
7	19.2	28.03	13.62	13.80	15.70	0.81	0.69	0.78	116.22	99.00	111.92	102	100	102
7	23.9	10.39	14.01	15.56	14.65	0.84	0.94	0.88	120.53	134.88	126.27	96	94	98
7	23.9	17.22	13.56	13.79	14.06	0.82	0.83	0.92	117.66	119.09	132.01	96	96	96
7	23.9	28.03	17.85	19.22	18.11	0.90	0.96	0.91	129.14	137.74	130.57	96	98	96
7	29.9	10.39	19.19	19.39	19.44	1.53	1.55	1.55	219.53	222.40	222.40	99	100	100
7	29.9	17.22	19.50	20.61	20.92	1.46	1.44	1.46	209.49	206.62	209.49	99	99	100
7	29.9	28.03	17.99	18.53	19.94	1.35	1.30	1.49	193.70	186.53	213.79	93	96	98
8	19.2	10.39	24.77	24.46	23.65	1.48	1.47	1.30	198.55	197.21	174.40	100	100	---
8	19.2	17.22	26.06	26.46	25.78	1.56	1.46	1.42	209.28	195.87	190.50	96	96	---
8	19.2	28.03	22.45	22.61	24.03	1.35	1.36	1.32	181.11	182.45	177.09	93	93	92
8	23.9	10.39	23.01	22.85	23.57	1.87	1.72	1.89	250.87	230.75	253.56	90	88	92
8	23.9	17.22	26.57	26.50	27.11	1.86	1.86	1.90	249.53	249.53	254.90	---	---	---
8	23.9	28.03	25.44	26.15	25.97	1.78	1.84	1.95	238.80	246.85	261.61	100	---	---
8	29.9	10.39	25.94	26.38	25.84	1.82	1.85	1.81	244.17	248.19	242.82	---	---	---
8	29.9	17.22	23.90	24.26	25.47	1.68	1.82	1.79	225.38	244.17	240.14	---	---	---
8	29.9	28.03	22.23	22.89	24.05	1.56	1.60	1.69	209.28	214.65	226.72	90	---	---
9	19.2	10.39	23.00	21.58	22.98	1.38	1.30	1.38	194.12	182.87	194.12	114	110	117
9	19.2	17.22	20.83	21.76	21.73	1.25	1.31	1.42	175.84	184.28	199.75	120	114	110
9	19.2	28.03	18.90	22.09	20.93	1.33	1.55	1.47	187.09	218.04	206.78	114	114	120
9	23.9	10.39	25.24	25.10	25.92	2.02	2.01	1.95	284.15	282.75	274.31	115	120	123
9	23.9	17.22	24.64	24.56	24.12	1.72	1.72	1.81	241.95	241.95	254.61	123	120	120
9	23.9	28.03	27.90	26.06	25.12	1.96	1.83	1.75	275.71	257.43	246.17	116	105	116
9	29.9	10.39	25.79	25.94	25.49	1.81	1.95	1.79	254.61	274.31	251.80	120	123	123

Subject	Air Temperature °C	Air Velocity m/min	Ventilation Rate l/min			Oxygen Consumption l/min			Metabolic Rate $Kcal/m^2/hr$			Heart Rate Beats/min		
9	29.9	17.22	25.75	25.18	24.24	1.81	1.76	1.85	254.61	247.58	260.24	118	114	118
9	29.9	28.03	22.55	24.59	25.53	1.58	1.72	1.79	222.26	241.95	251.80	120	116	110
10	19.2	10.39	26.75	27.22	27.18	1.87	1.77	1.90	263.17	249.10	267.39	130	126	108
10	19.2	17.22	27.01	28.18	28.69	1.89	1.83	1.86	265.99	257.54	261.76	136	130	135
10	19.2	28.03	23.08	28.17	25.11	1.73	1.83	1.51	243.47	257.54	212.51	124	116	114
10	23.9	10.39	29.47	29.99	32.98	2.06	1.95	1.98	289.91	274.43	278.65	---	---	---
10	23.9	17.22	26.51	29.99	30.61	2.12	2.40	2.11	298.35	337.76	296.95	123	129	126
10	23.9	28.03	32.55	30.32	31.24	2.12	1.97	2.03	298.35	277.24	285.69	126	126	132
10	29.9	10.39	26.13	26.19	26.37	2.09	1.96	1.85	294.13	275.84	260.36	120	120	117
10	29.9	17.22	27.77	30.19	31.26	1.94	1.96	2.03	273.02	275.84	285.69	132	132	129
10	29.9	28.03	29.70	29.72	32.48	2.08	2.08	2.28	292.73	292.73	320.87	124	128	132
11	19.2	10.39	17.02	19.56	19.75	1.36	1.57	1.48	204.70	236.31	222.76	106	111	---
11	19.2	17.22	25.53	25.26	25.44	1.53	1.52	1.53	230.29	228.78	230.29	112	112	116
11	19.2	28.03	22.34	23.93	23.17	1.46	1.44	1.39	219.75	216.74	209.21	110	120	112
11	23.9	10.39	23.27	24.75	26.57	1.52	1.49	1.60	228.78	224.26	240.82	116	117	117
11	23.9	17.22	24.74	25.10	27.37	1.49	1.51	1.64	224.26	227.27	246.84	116	116	118
11	23.9	28.03	26.53	26.85	26.83	1.59	1.61	1.61	239.39	242.33	242.33	120	116	122
11	29.9	10.39	28.26	28.59	28.72	1.98	2.00	2.01	298.02	301.03	302.53	126	124	128
11	29.9	17.22	26.33	25.18	26.84	1.84	1.76	1.88	276.94	264.90	282.96	120	120	126
11	29.9	28.03	26.07	26.95	28.22	1.69	1.62	1.69	254.37	243.83	254.37	120	120	126
12	19.2	10.39	25.76	24.99	26.10	1.16	1.00	1.05	176.64	152.28	159.89	104	108	102
12	19.2	17.22	21.87	22.14	23.21	1.42	1.32	1.27	215.71	201.59	193.75	102	100	100
12	19.2	28.03	23.65	23.81	25.14	1.30	1.19	1.26	197.96	181.21	191.87	104	106	102
12	23.9	10.39	24.42	24.19	24.34	1.10	1.21	1.10	167.36	184.21	166.77	104	99	105
12	23.9	17.22	31.32	28.54	31.22	1.57	1.43	1.24	239.08	217.76	189.51	105	102	112
12	23.9	28.03	25.16	25.80	25.47	1.26	1.29	1.27	191.34	196.18	193.73	104	108	111
12	29.9	10.39	23.06	24.58	25.22	1.62	1.72	1.76	246.69	261.92	268.01	108	112	114

Subject	Air Temperature °C	Air Velocity m/min	Ventilation Rate l/min			Oxygen Consumption l/min			Metabolic Rate Kcal/m^2/hr			Heart Rate Beats/min		
12	29.9	17.22	22.01	22.22	22.60	1.54	1.55	1.58	234.51	236.03	240.60	102	104	106
12	29.9	28.03	22.06	22.44	23.20	1.55	1.57	1.63	236.03	239.08	248.21	102	106	110
13	19.2	10.39	21.57	21.65	21.01	1.08	1.09	1.05	162.10	163.60	157.60	96	114	114
13	19.2	17.22	20.19	19.78	20.76	1.22	1.19	1.15	183.11	178.69	172.61	88	90	87
13	19.2	28.03	19.80	21.37	22.28	1.09	1.06	1.22	162.87	159.79	183.79	81	105	92
13	23.9	10.39	20.15	22.39	21.97	1.21	1.46	1.32	181.61	219.14	192.12	114	118	120
13	23.9	17.22	19.43	20.57	21.45	1.27	1.24	1.29	190.60	186.11	193.62	112	111	112
13	23.9	28.03	18.22	20.42	20.75	1.18	1.22	1.24	177.17	183.22	186.19	111	114	114
13	29.9	10.39	11.07	10.83	11.52	0.83	0.82	0.92	124.58	123.08	138.09	118	120	120
13	29.9	17.22	11.78	12.50	12.19	0.89	0.94	0.86	133.58	141.09	129.08	118	118	124
13	29.9	28.03	15.22	15.55	18.76	1.22	1.09	1.31	183.11	163.60	196.62	114	116	114
14	19.2	10.39	5.78	6.23	6.32	0.37	0.37	0.35	65.15	64.73	60.25	114	114	114
14	19.2	17.22	4.77	5.23	5.45	0.26	0.26	0.27	45.54	45.38	47.26	114	108	108
14	19.2	28.03	4.41	4.37	4.55	0.22	0.24	0.23	38.20	41.69	39.40	120	114	120
14	23.9	10.39	6.41	6.69	7.07	0.38	0.40	0.42	66.44	69.33	73.28	111	114	114
14	23.9	17.22	5.81	5.66	5.62	0.35	0.31	0.34	60.39	53.91	58.46	114	112	111
14	23.9	28.03	6.46	6.31	6.03	0.45	0.38	0.36	78.33	65.56	62.67	114	111	111
14	29.9	10.39	5.88	6.59	6.82	0.38	0.39	0.41	66.02	68.28	70.67	120	122	122
14	29.9	17.22	5.97	5.96	6.28	0.38	0.38	0.37	66.94	66.84	64.95	122	117	120
14	29.9	28.03	5.73	5.59	5.40	0.40	0.39	0.35	69.19	67.60	60.55	114	114	116
15	19.2	10.39	11.79	12.27	11.75	0.59	0.61	0.58	80.21	83.54	79.98	90	92	92
15	19.2	17.22	11.65	11.79	11.00	0.52	0.53	0.49	71.44	72.30	67.43	92	90	90
15	19.2	28.03	11.24	11.06	11.40	0.61	0.55	0.57	84.22	75.37	77.69	88	90	92
15	23.9	10.39	9.13	10.73	10.85	0.45	0.53	0.54	62.11	73.03	73.83	93	93	92
15	23.9	17.22	10.18	9.53	8.13	0.56	0.52	0.48	76.13	71.24	66.28	90	88	92
15	23.9	28.03	10.01	9.88	11.99	0.50	0.49	0.60	68.10	67.23	81.60	96	93	88
15	29.9	10.39	10.98	11.17	11.47	0.54	0.55	0.57	74.59	75.94	77.97	87	93	92

Subject	Air Temperature °C	Air Velocity m/min	Ventilation Rate l/min			Oxygen Consumption l/min			Metabolic Rate Kcal/m^2/hr			Heart Rate Beats/min		
15	29.9	17.22	11.63	11.93	11.77	0.64	0.71	0.64	87.72	97.32	87.72	96	92	90
15	29.9	28.03	11.75	11.88	11.30	0.70	0.71	0.68	95.95	97.32	93.20	88	92	90
16	19.2	10.39	12.68	12.83	13.21	0.57	0.57	0.53	77.06	77.95	71.36	112	114	114
16	19.2	17.22	12.06	12.15	12.98	0.60	0.60	0.58	81.42	82.01	78.85	112	114	114
16	19.2	28.03	11.07	11.50	11.27	0.61	0.57	0.56	82.43	77.80	76.28	111	111	112
16	23.9	10.39	11.43	12.20	12.21	0.51	0.55	0.55	69.51	74.20	74.26	112	114	116
16	23.9	17.22	12.78	12.98	13.28	0.64	0.65	0.59	86.28	87.66	80.70	114	114	114
16	23.9	28.03	11.84	10.69	11.36	0.53	0.53	0.51	72.23	72.46	69.29	114	114	114
16	29.9	10.39	12.27	11.90	12.29	0.67	0.65	0.68	91.59	88.77	91.71	116	114	116
16	29.9	17.22	12.63	12.92	13.11	0.76	0.78	0.79	103.24	105.95	107.31	117	117	120
16	29.9	28.03	11.90	12.62	12.41	0.72	0.76	0.75	97.80	103.24	101.88	117	120	118